STUDY ON POWER DISTRIBUTION NETWORK AUTOMATION TO MITIGATE POWER OUTAGES

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ABSTRACT

The paper presents development of an appropriate distribution system automation to mitigate power outages and improve reliability of the system. Addis Ababa distribution system is taken as a case study to demonstrate the effectiveness of the proposed technique. It is found that 55% of the number of interruptions and 46% of the total duration of interruptions in the existing Addis Ababa distribution system are due to distribution system related problems. The proposed distribution system automation is capable of detecting feeder faults, determining the fault location, isolating the faulty section of the feeder and finally restoring power supply to healthy portions of the feeder. Thus, it has the capacity to significantly improve the reliability of the distribution system.

The performance of the designed model is evaluated through simulation studies to check the reliability improvement of Addis Ababa distribution network. The simulation results show that the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) is improved by 69% and 88%, respectively. Thus, it is observed that the frequent interruptions and outages in the existing Addis Ababa distribution system could be potentially mitigated by implementing the proposed automation of Addis Ababa distribution network.

Key Words: Distribution Automation, Distribution Network, Medium Voltage Line, Interruption, Power Outage, Reliability.

INTRODUCTION

Electric power distribution system is an important part of electrical power systems that determines supply reliability or proper delivery of electricity to consumers.

Generally speaking, customer expectations on supply reliability are steadily increasing [1]. The owners of distribution network are being required to improve the reliability of power delivery through making the whole operating condition more efficient. In some cases, explicit power quality criteria are even included in negotiated contracts between customers and utilities[1]. Moreover, in liberalized markets, regulators typically require the utilities to report on the reliability performance or even penalize them in case of violations in several countries [2].

Distribution Automation (DA) is the remote control of switches to locate, isolate faults and restore the service, when a fault occurs in the power distribution line. It also results into a highly reliable, self-healing power system that responds rapidly to real-time events with appropriate actions [3, 4]. This concept combines the ability to mix local automation, remote control of switching devices, and central decision making into a cohesive, flexible, and cost-effective operating architecture for power distribution systems[5].

Automation in the distribution field allows utilities to implement flexible control of distribution systems, which can be used to enhance efficiency, reliability and quality of electric service [1,3,6]. From the analysis of Recloses and Sectionalizers, it is found that there is a significant improvement in the reliability of a distribution feeder and as a result, coordinated system of these devices can significantly improve the reliability indices SAIDI and SAIFI[1,6].

The successful implementation of DA system results mainly in Operational & Maintenance benefits, financial benefits, and customer related benefits[3]. These benefits are related to the improved reliability, reduced operation and maintenance expenses, reduced fault location time, increased revenue due to quick restoration, reduction in staffing, enhanced system efficiencies and consumer satisfaction.

The above cited researches clearly reveal the importance of the technology in addressing mainly, reliability and efficiency issues for the specified distribution networks, but before deciding to go ahead with the technology, the potential drawbacks, interruption causes, power outage levels and shortcomings of the old system should be studied in detail. Then, it should be verified that these identified problems could be mitigated by deploying DA for that specific utility company or distribution network. The aim of this research is, therefore, to develop an appropriate distribution automation model that can potentially mitigate the power outages occurring on the existing Addis Ababa distribution system.

Case Study: Present State of Addis Ababa Distribution Network

Power distribution network in Addis Ababa is effected at a primary voltage of 33 and 15kV consisting entirely of 3-phases, 3-wire feeders and is stepped down to a utilization voltage of 380/220V (3-phase, 4 wire) and 500V for some industries using 3-phase transformers to customer's level. The distribution system in Addis Ababa consists of 32,373.39 km of 33kV and 15kV; 95,000km of 380/220V lines and 6,339 distribution transformers[3]. Even though, there are many efforts and launched projects to modernize Addis Ababa's underground electric cable installation, the medium voltage (MV) and Low Voltage (LV) networks are still dominated by overhead lines.

In the radial distribution network structure of Addis Ababa, there are manually controlled three phase switches (MCOS) or section switches located on the beginning of each branch circuit that can interrupt the supply for planned outages like maintenance or unplanned outages of various disturbances. But, the network is not suited with additional equipments such as remote controlled switches, automatic reclosers, sectionalizes, remotely controlled fault passage indicators, etc. which would contribute a lot in improving the overall reliability. In a radial distribution system, only one path is connected between each customer and the substations. i.e. The electrical power flows from the substation to the customer along a single path which if interrupted results in complete loss of power to the customer. Such system has only one power source for a group of customers and is usually suitable for sparsely populated areas. For a city like Addis Ababa, with a population density of 5,165.1/km^2 and with a huge power demand such kind of network configuration is unsuccessful and that was exactly what has been witnessed for the past years. On top of this, the whole system can only be operated manually which makes it difficult to monitor the system state as well as to take any action.

Knowing this, Ethiopian Electric Utility, EEU (formerly known as Ethiopian Electric Power Corporation, EEPCo) planned to modify the system to a ring system by installing several switching stations in between various substations [7]. However, only few of the total number of feeders per substation, which are believed to encounter many faults, have been made to interconnect to other substations.

In the existing distribution system, pinpointing the exact or even approximate location of faults is difficult, even though fault passage indicators are installed in various switching stations. Dispatchers still depend on telephone calls from customers and substation Operators. Customers' calls only provide an approximate location of the outage. Once the approximate location of outages is known, line crews are dispatched to drive along the lines to look for damage. After the damaged area is located, it has to be isolated from the rest of the system if the fuse protecting that line has not operated. This is done by first opening the substation breaker and then manually operating the switches or removing the fuses. Coordination between the line crews and dispatchers is maintained via portable radio to perform this task properly or via mobile telephone. The next step is to restore power to those parts of the system which are undamaged but have lost power because of problems elsewhere in the system. The power to these parts may be provided from alternates routes. The dispatchers determine such possible routes and ask the line crew to operate the isolators. Most of the isolators cannot be operated under load; therefore, the substation breaker is opened before operating the isolators. Since the whole process is done manually, it takes a long time. This is depicted in figs. 1 and 2. Automation of this function requires installation of devices such as reclosers, remotely controlled Sectionalizers and installation of sensors on the feeders and/or at customer locations to detect interruption of service.

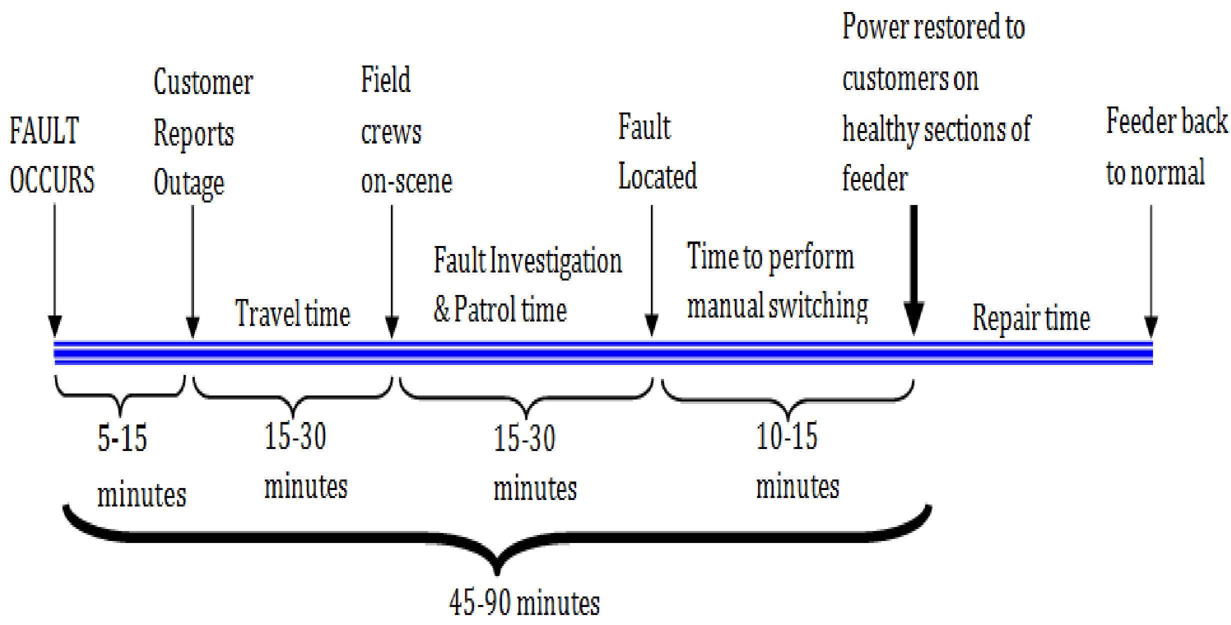

Fig. 1: Activity-time diagram for a permanent feeder fault without automation

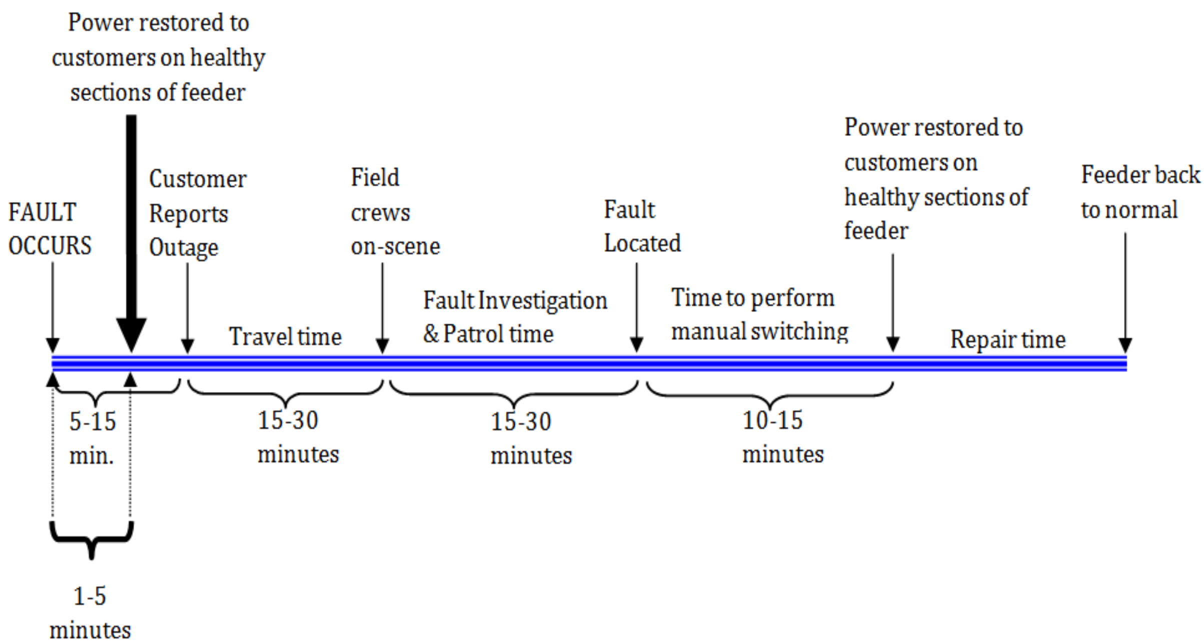

Fig. 2: Activity-time diagram for a permanent feeder fault with proposed automation model

Reclosers

A recloser is a device with the ability to detect phase and phase-to-ground overcurrent conditions, to interrupt the circuit if the overcurrent persists after a predetermined time, and then to automatically reclose to re-energize the line. If the fault that originated the operation still exists, then the recloser will stay open after a preset number of operations, thus isolating the faulted section from the rest of the system. Thus, the recloser, with its opening/closing characteristic, prevents a distribution circuit being left out of service for temporary faults.

Reclosers are used at the following points on a distribution network:

- In substations, to provide primary protection for a circuit,
- In main feeder circuits, in order to permit the sectioning of long lines and thus prevent the loss of a complete circuit due to a fault towards the end of the circuit,

- In branches, to prevent the tripping of the main circuit due to faults on the spurs.

Sectionalizers

A sectionalizer is a device that automatically isolates faulted sections of a distribution circuit once an upstream breaker or recloser has interrupted the fault current and is usually installed downstream of a recloser. Since sectionalizers have no capacity to break fault current, they must be used with a back-up device that has fault current breaking capacity. Sectionalizers count the number of operations of the recloser during fault conditions. After a preselected number of recloser openings, and while the recloser is open, the sectionalizer opens and isolates the faulty section of the line.
Therefore, the switching needed to restore power to unfaulted parts of the system can be accomplished remotely. Moreover, since the location of the outage is known, the crew is sent to the precise location instead of asking to go in a general area. Thus, the whole process of outage location and service restoration can be accomplished more efficiently by less people in much less time.

Power interruptions in the Existing Addis Ababa Distribution System

The frequency and duration of interruptions occurring on the different feeders of Addis Ababa distribution system are given in Table 1 and plotted in figs. 3 and fig. 4, respectively. The system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI) are calculated as discussed below and are listed in Table 3.

a) System Average Interruption Duration Index (SAIDI)

This index measures the total duration of an interruption for the average customer during a given time period. To calculate SAIDI, each interruption during the time period is multiplied by the duration of the interruption to find the customer-hrs/mins of interruption. The customer-hrs/mins of all interruptions are then summed to determine the total customer-hrs/mins. To find the SAIDI value, the customer-hrs are divided by the total customers served.
The formula is,

$$SAIDI = \frac{\sum(r_i \times N_i)}{N_T}$$

Where,
r_i=Restoration time (hrs./mins.)
N_i=Total number of customers interrupted
N_T=Total number of customers served

b) System Average Interruption Frequency Index (SAIFI)

The System Average Interruption Frequency Index (SAIFI) is the average number of times that a system customer experiences an outage during the year or time under study. The SAIFI is found by dividing the total number of customers interrupted by the total number of customers served.
SAIFI is found as:

$$SAIFI = \frac{\sum(N_i)}{N_T}$$

Where,
N_i=Total number of customers interrupted
N_T=Total number of customers served

From table 1, it can be seen that the annual SAIDI is about 209 Hrs., which means that on the average each customer in Addis Ababa was without power supply for 209 Hrs. due to interruptions on MV- feeders during that year. It can also be seen that the annual SAIFI is about 184, indicating power for each customer in Addis Ababa has been interrupted on the average 184 times in a year. According to the reliability standard set by Ethiopian Energy Authority (formerly known as Ethiopian Electricity Agency)[8], these reliability indices clearly illustrate that the reliability of the power network is very poor.

Causes of Interruptions

The faults in the electricity network may have various forms as illustrated in table 2. These faults could be mainly of two types, namely, transient (temporary) and permanent faults. Usually, transient faults occur when phase conductors electrically contact other phase conductors or ground momentarily due to trees, birds or other animals, high winds, lightning, flashovers, and so on. Transient faults are cleared by a service interruption of sufficient length of time to extinguish the power arc or electric discharge. Here, the fault duration is minimized and unnecessary fuse blowing is prevented by using instantaneous or high-speed tripping and automatic reclosing of a relay-controlled power circuit breaker or the automatic tripping and reclosing of a circuit recloser [9].

The breaker speed, relay settings and recloser characteristics are selected in a manner to interrupt the fault current before a series fuse is blown, which would cause the transient fault to become permanent. Permanent faults are those which require repairs by repair crew in terms of [9]:

- Replacing burned-down conductors, blown fuses, or any other damaged apparatus
- Removing tree limbs from the line
- Manually reclosing a circuit breaker or recloser to restore service

From Fig. 5 pie chart plot, it can be seen that, 55% of the total number of power interruptions are due to distribution related problems such as Distribution Permanent Earth Fault (DPEF), Distribution Permanent Short Circuit (DPSC), Distribution Transient Earth Fault (DTEF), Distribution Transient Short Circuit (DTSC), Distribution Line Over Load (DLOL) and the rest 45% are due to others like generation, transmission problems and operational or intentional isolation.

Fig. 6 pie chart plot shows the duration of interruption in Addis Ababa based on specific fault type. Similarly, it can be seen that 45.92% of the total duration of interruptions are due to distribution related problems and the rest 54.08% are due to others as mentioned above. The above percentage figures clearly demonstrate that distribution related problems account significant share for the cause of the interruptions which can be improved by employing appropriate mitigating technology.

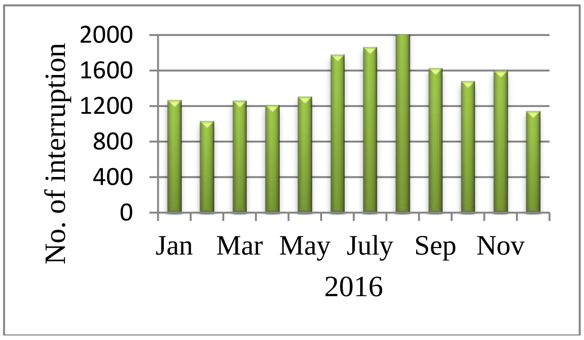

Fig. 3: Frequency of interruption in Addis Ababa at feeder level, (Source: EEU)

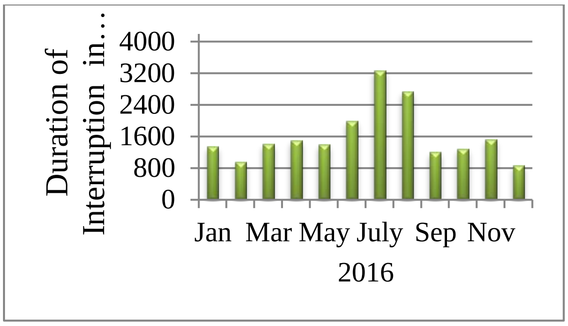

Fig. 4: Duration of interruption in Addis Ababa at feeder level, (Source: EEU)

Overview of Proposed Automated Feeder System

Fig. 7 demonstrates the proposed model for the automated feeder system to detect feeder faults, determine the fault location, isolate the faulted section of the feeder and finally restore service to healthy portions of the feeder.

The local scheme involves detection, location of the fault and isolation of the affected area through various field components. Whereas, the centralized scheme which involves the central station is needed to monitor and restore the service of the feeder system.

The main components to be needed for the feeder automation are protection relay (R), automatic reclose (RC), sectionalized (S) and tie switches (Tie) or load break switch. The number of sectionalizes considered in this model are four, but it may vary depending on the total length of the feeder and loading level in each section.

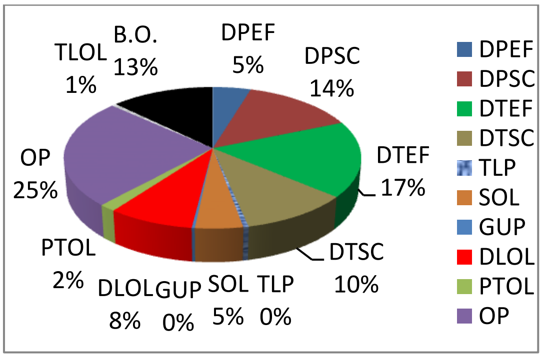

Fig. 5: Average percentage of Frequency of interruption

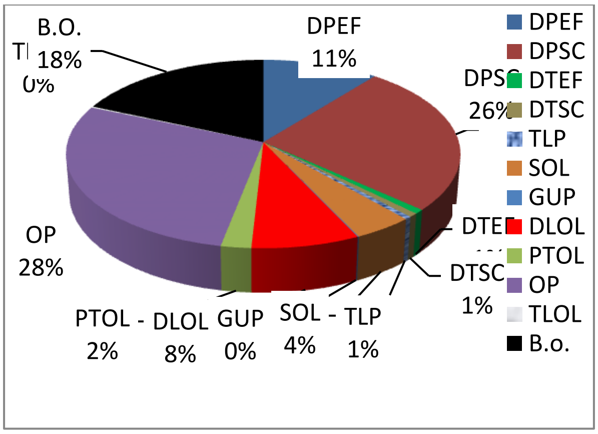

Fig. 6: Average percentage of Duration of interruption for feeders in Addis Ababa based on fault type.

In the model, three medium voltage lines or outgoing feeders from the same substation or neighboring substations are considered for interconnection, so that, it is possible to restore the service to the healthy sections of the contingent feeder from either of the remaining two routes by taking their loading into consideration. i.e. The operator checks which feeder is strong enough to carry the additional load and closes the respective tie switch to restore the service to the healthy section of the contingent feeder. When a transient fault occurs at any of the sections, the assigned/responsible recloser will try to reclose the circuit automatically and restores the feeder to its normal condition. If a permanent fault occurs in either of the sections, the recloser will lock out after its third trial and the fault detectors which employ fault location algorithm by taking the network structure information and obtained measurements of fault currents and voltages as input located at each of the sectionalizers will detect the fault, report and give flash. Then, the nearby sectionalizers surrounding the fault will automatically open which makes the faulted section to be isolated. After that, the operator closes the circuit breaker and simultaneously checks whether the alternate feeder can carry the additional load (downstream to the isolated section) of the faulty feeder. Finally, the operator will remotely close the respective tie switch which will supply the disconnected load until the permanent fault is cleared. All of the above activities including the coordination of the protective and isolation devices are discussed in detail in the next sections.

SIMULATION RESULTS AND ANALYSIS

The protection scheme of a 15kV distribution feeder feeding loads at different sections is done with Tavrida Electric Automated Relay Manager (TELARM) software tool as shown in fig. 8. Only four sections are considered for the ease of demonstration and the same principle can be applied to any number of sections whenever needed. It is assumed that the recloser will lockout after 4 number of trips with reclosing times 1, 5, 10 and 60 sec. for first, second, third and reset reclosings respectively. Sectionalizers S1, S2 and S3 are set at 3, 2 and 1 shot respectively. If the autorecloser trips the fourth time (after the third reclosing shot), the fault is regarded as permanent. Hence, further autorecloser operation is locked out. During the process of auto reclosing, various sections would be removed out of the line with the help of sectionalizers to power the healthy portion of the feeder. If the fault is permanent in nature, then the automation control unit can intervene to restore the service to healthy sections from other alternative feeders by sending remote switching commands to sectionalizers.The cycle of switching of the different reclosers and sectionalizers is described during this time as follows. Fig. 9 presents the state of the reclosers and sectionalizers under permanent fault at section 3 (between S2 and S3) by using different colors where green represents closed state, violet represents open state, yellow represents reclose time, blue represents tripping time and red represents open and lockout state. Primarily, R performs the first reclosing cycle and trips again as presented above. Then, R times out for 5 seconds and S3 trips and locks out. Then, R closes for a second time. S2 and S1 sense the control voltage and close the first time. A fault current passes through R and R trips for the third time and times out for 10 seconds. At this point, the control voltage is lost and S2 trips the second time and locks out. Finally, R closes for the third time and the fault on section 03 is isolated. The Operator in control unit will try to remotely close S2 and S3 after clearance of the permanent fault. Similarly, all transient and permanent faults are created at various sections of the feeder for demonstrating the responses of the various switching and protection devices installed throughout the feeder.

Table 1: Frequency and duration of interruption in Addis Ababa at all feeders, (Source: EEU)

No.	Period	Frequency of Interruption (No.)	Duration of Interruption (Hr.)	SAIDI Values (hrs./customer)	SAIFI Values (no./customer)
1.	Jan, 2016	1,265	1,348.58	13.50	12.39
2.	Feb, 2016	1,029	953.88	9.35	10.64
3.	Mar, 2016	1,260	1,413.15	14.26	12.42
4.	Apr, 2016	1,210	1,507.03	19.22	12.10
5.	May, 2016	1,308	1,402.55	14.12	14.94
6.	June, 2016	1,781	2,001.22	22.96	18.02
7.	July, 2016	1,864	3,280.00	34.50	19.06
8.	Aug, 2016	2,363	2,742.00	28.49	22.36
9.	Sep, 2016	1,628	1,208.00	11.89	17.96
10.	Oct, 2016	1,483	1,290.00	11.95	15.32
11.	Nov, 2016	1,596	1,527.00	19.87	17.15
12.	Dec, 2016	1,145	872.00	8.85	11.31
Total (year 2016)		17,932	19,545.61	209	184

Table 2: Acronyms and Description of Faults System

Fault Acronym	Fault Type
DPEF	Distribution Permanent Earth Fault
DPSC	Distribution Permanent Short Circuit
DTEF	Distribution Transient Earth Circuit
DTSC	Distribution Transient Short Circuit
TLP	Transmission Line Problem
SOL	System Over Load
GUP	Generation Unit Problem
DLOL	Distribution Line Over Load
PTOL	Power Transformer Over Load
OP	Operational (Intentional)
TLOL	Transmission Line Over Load
B.O.	Blackout

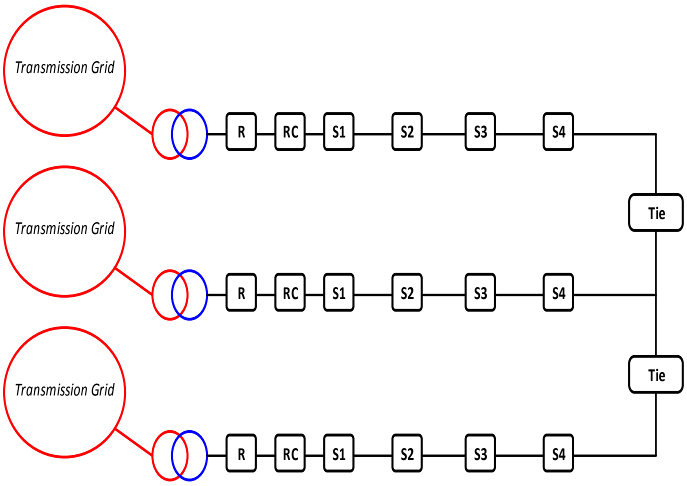

Fig. 7: Model of proposed Automated Feeder

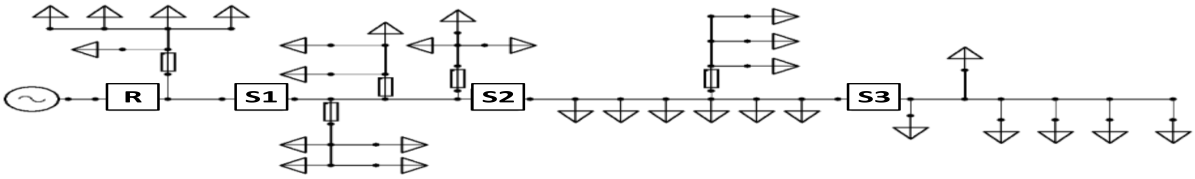

Fig. 8: Single line diagram of a Feeder Obtained using TELARM

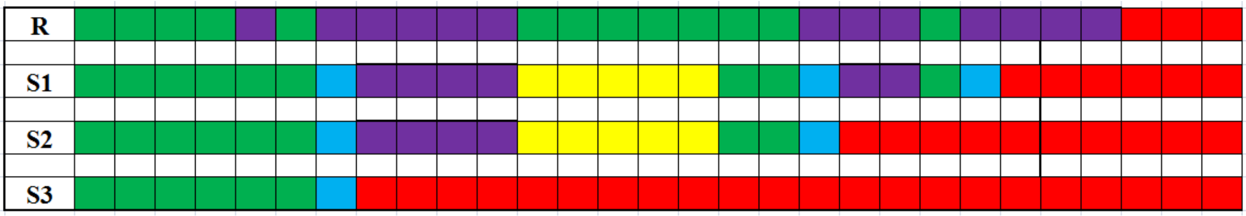

Fig. 9: Simulation result: State of Recloser and Sectionalizers under permanent fault at section 3

(Green indicates closed position, violet indicates open position, blue indicates tripping time, yellow indicates reclose time and red indicates open & lockout)

Table 3: Comparison of reliability indices of the existing feeder and the proposed automated system

No.	Reliability Index	Average standard reliability indices of the existing feeder system	Average standard reliability indices of the proposed model
1.	Annual SAIDI (hrs.)	21.67	5.611
2.	Annual SAIFI (no.)	30.22	3.117

CONCLUSIONS

The reliability analysis of the existing Addis Ababa distribution system reveals that around 55% of the total number of power interruptions are due to distribution system related problems and the rest 45% are due to others like generation, transmission problems and operational interruptions. Similarly, around 46% of the total duration of interruptions are caused by distribution system related problems and the rest 54% are due to the others.

Thus, it is observed that majority of the power interruption problems are related to the existing distribution system network. The effectiveness and potential benefits of implementing distribution system automation, specifically feeder automation to the distribution network of Addis Ababa, is investigated through simulation studies of the existing distribution system with proposed automation. The simulation results presented in Table 3 reveal that with the proposed distribution system automation, the system average duration index SAIDI) is improved by more than 69% and the system average frequency index (SAIFI) is improved by more than 88% as compared to those of the existing distribution system. These results clearly demonstrate that the system automation is capable of potentially mitigating the frequent interruptions and outage problems occurring in the existing Addis Ababa distribution system.

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